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COLLEGE OF ENGINEERING
NAVAL ARCHITECTURE AND OFFSHORE ENGINEERING

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December 28, 1990

Dr. Edwin Rood
Director, Fluid Mechanics
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Office of Naval Research
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800 N. Quincy Street
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Final Technical Report of Contract N00014-88K-0002
UCB ORS# GZ-25801

Dear Edwin:

This final technical letter report for the referenced contract consists of four sections. Section 1 gives the relevant contract information. Brief summaries of the major projects and of the significant accomplishments achieved during the contract period are given in section 2. A list of publications and technical reports, including doctoral dissertations, is provided in section 3. Section 4 lists the professional honors awarded to the investigators of this contract.

1. ONR Contract Information

Contract Title:	Nonlinear Bow Flows and Waves
Contract Number:	N00014-88-K-0002
Work Unit Number:	4326-003 or 4322-802
Scientific Officer:	Dr. Edwin Rood
Contract Period:	10/1/87 - 9/30/90
Report Date:	12/28/90

Principal Investigators & Cognizant Organization:

PI:	Ronald W. Yeung
Co-Investigator:	William C. Webster
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2. Major Projects and Scientific Accomplishments

2.1 Flow Structure in Front of a Ship Bow

Investigators: Prof. R.W. Yeung, Mark Grosenbaugh, P. Ananthakrishnan, Scott Coakley

The primary goal of the study is to develop the necessary mathematical, numerical and experimental techniques to understand the intricate mechanics of bow flow. During the first contract year, the Ph.D. thesis of Mark Grosenbaugh was completed. The theoretical and numerical model that describes the nonlinear waves in front of the bow was detailed in the paper entitled "Nonlinear free-surface flow at a two-dimensional bow", was published in the *Journal of Fluid Mechanics*. Experimental work describing the properties and characteristics of the free-surface separation point and the phenomenon of bow-wave oscillation was described in the *Journal of Ship Research*. A synopsis of these two works, together with a scaling technique that attempted to amalgamate the theoretical and experimental finding, was presented in a paper at the 17th ONR Symposium (Grosenbaugh & Yeung, 1988). Grosenbaugh is now an Assistant Scientist at the Woods Hole Institution of Oceanography, Mass.

Continuing efforts on this problem in the last 2 years have been directed towards developing methods to solve the viscous-flow solution in the slow-moving zone just ahead of the bow. To handle this, we have developed a variational grid-generation procedure, the successful application of which to inviscid flow have been reported in two occasions: Yeung & Ananthakrishnan (1989) and Yeung & Vaidhyanathan (1990), for treating problems of submerged bodies. Steady progress in applying this grid-generation methodology to solve the Navier Stokes equations have been made. Using a projection-type method, we have been able to obtain results at relatively high Reynold number, $O(10^4)$. A comprehensive set of results will be documented in the thesis of Ananthakrishnan.

At the beginning of the third year of study, an investigation complementary to the above local-bow flow study has been initiated by a new Ph.D. student, Scott Coakley. The primary objective is to examine the global three-dimensional flow picture. Coakley has successfully developed bi-cubic surface splines to represent the nonlinear free surface. Efficient methods for handling a large-scale system of unknowns that is of order 10,000 are also being studied. An investigation of the numerical properties of a number of high-order radiation conditions that are applicable to this type of problems is also anticipated.

2.2 Wave-Viscosity Interaction for Bodies in a Free Surface

Investigators: Prof. R. W. Yeung & C.-F. Wu

In this study, the Navier-Stokes equations were solved analytically with the assumption that the ratio of the motion amplitude of body oscillations to the wavelength is small. This allows the convective terms of the viscous-flow equations to be neglected, yet both kinematic and dynamic boundary condition on the free surface can still be modeled. Using the method of Green functions, vorticity and divergent source functions were derived, with a frequency-Reynold number as the viscous parameter. Exploiting these analytical forms, Wu (1990) has completed a doctoral dissertation entitled "Wave Viscosity Interaction for Bodies in a Free Surface". The work describes in detail how traditional hydrodynamic quantities such as added mass and damping may be affected by viscosity. This original research should be particularly valuable to experimenters for assessing the scale effects of model testing. Further, this quasi-analytical solution will be useful as a benchmark test for more extensive

numerical works such as those being carried out in section 2.1 above. A manuscript on these new findings has been accepted for presentation in a 1991 ASME conference.

Earlier, before Wu started on his doctoral work, he has assisted in developing an impulse-response technique for the prediction of the nonlinear resonant frequencies of two-dimensional wave basins (Yeung & Wu, 1989a). This work has subsequently led to a short analytical study on the singular behavior of the body and free surface intersection point, which was described in an invited lecture (Yeung & Wu, 1989b) presented at a meeting held in honor of German fluid dynamicist K.Wieghardt. C.-F. Wu has recently accepted a Research Scientist position at the National Research Council of Canada, Newfoundland.

2.3 Application of Fluid-Sheet Theory to Flows with Surface Tension
Investigators: Prof. W. C. Webster & A. Ekvall

Anders Ekvall has completed a dissertation entitled "Application of the Method of Fluid Sheets to Flows with Surface Tension" (Ekvall, 1989). initially, the objective of the work was to study the spray sheet off a planing bow. However, a preliminary study based on the first-level Green-Naghdi equations appeared to suggest that it does not yield a well posed system; hence no further work on that problem ~~was carried~~ out. This resources was then directed instead to study the problem of roll ~~waves~~ on an incline plane. It is concluded that the level-III governing equations ~~predict~~ the linear stability properties very well. The kinematic approximation ~~of~~ such theory appear to start to yield some discrepancies at Reynold number larger ~~than~~ 100. Numerical solution of the a level-III type equations for nonlinear waves agree qualitatively very well with some published experimental findings. In particular, the breakdown of an initial solitary disturbance into a series of waves, observed earlier by others, is predicted by the computations. A manuscript for this work is under preparation. A. Ekvall is now a research engineer at *Shell Oil*, Houston.

2.4: Fluid-sheet theory Application to Nonlinear Wave Problems.
Investigators: Prof. W. C. Webster & D. Y. Kim

Do Young Kim has completed a Ph.D. thesis entitled "A Nonlinear Theory of Water Waves by Direct Methods" (Kim, 1989). In this thesis, the earlier work of Jonathan Shield on solitary waves was extended to include surface tension. The advantage of the fluid-sheet approach lies in its ability to predict the shape of the solitary waves near the critical value of τ close to 1/3. τ is a "surface tension to gravitational force factor". Previous and competing theories could not do so because they were normally based on some sort of "long-wave" assumptions. Fluid-sheet theory does not contain such an assumption. Kim has also extended the Green and Naghdi equations to level II for periodic waves. It is apparent that these equations predict the basic characteristic of nonlinear waves well, when compared with known nonlinear solutions.

Two papers on fluid-sheet works have been completed in this area. First, a paper entitled "Application of high-level, Green-Naghdi Theory to fluid-flow problems" was presented at the IUTAM symposium. The work (Webster & Shields, 1990) follows closely the rather successful Level-II fluid-sheet theory for shallow-water developed earlier by J. J. Shields. Applications to the problem of shoaling of unsteady waves on a beach and to the problem of wave reflection at the end wall of a deep tank were made. A second paper entitled "The dispersion of large-amplitude gravity waves in deep water", was presented at the 18th ONR Symposium (Webster & Kim, 1990). In a manner similar to the Kim (1989), a level III theory based on an exponential shape factor in the vertical direction is introduced to simulate a train of steep regular as well as irregular waves. Nonlinear interactions of wave components commonly observed, due primarily to effects of large-amplitude dispersion, are well

reproduced by the theory. D. Y. Kim is a now a post-doctoral fellow at Seoul National University, S. Korea.

3. List of Publications in Alphabetical Order of Authors

Ekvall, A. (1989). "Application of the Method of Fluid Sheets to Flows with Surface Tension", Ph. D. Dissertation, College of Engineering, Univ of California, Berkeley, May.

Kim, D. Y. (1989). "A Nonlinear Theory of Water Waves by Direct Methods" by Do Young Kim, Ph. D. Dissertation, College of Engineering, Univ of California, Berkeley, May.

Grosenbaugh, Mark (1987). "Nonlinear Flow at the Bow of a Ship: An Experimental & Theoretical Investigation," Ph. D. Dissertation, College of Engineering, Dept of Naval Arch & Offshore Engrg., Univ of California, Berkeley, December.

Grosenbaugh, M. & Yeung, R. W. (1988a). "Nonlinear Free-surface Flow at a Two-dimensional Bow", *Proceedings*, 3rd Int'l Workshop on Water Waves & Floating Bodies, April 10-13, Woods Hole, Mass.

*Grosenbaugh, M. & Yeung, R. W. (1988b). "Nonlinear Bow Flows - An Experimental & Theoretical Investigation", 17th Symp. Naval Hydrodyn., The Hague, The Netherlands, August 29, 1988.

*Grosenbaugh, M. A. & Yeung, R. W. (1989c). "Flow Structure near the Bow of a Two-Dimensional Body", *J. Ship Research,* vol 33, no. 4, pp. 269-283.

*Shiels, J. J. & Webster, W. C. (1989). "The Conservation of Mechanical Energy and Circulation in the Theory of Fluid Sheets", *J. Engrg Math.,* vol. 23, 1-15.

*Webster, W. C. & Shields, J. J. (1990) "Applications of High-level Green-Naghdi Theory to Fluid Flow Problems", *Proceedings,* IUTAM Memorial Symposium for R. E. D. Bishop, London, June.

*Webster, W. C. & Kim, D-Y. (1990) "The Dispersion of Large-Amplitude Gravity Waves in Deep Water", *Proceedings*, 17th Symposium on Naval Hydrodynamics, Ann Arbor, August.

Wu, C.-F. (1990) "Wave-Viscosity Interaction for Bodies in a Free Surface", Ph.D. dissertation, Dept. of Naval Architecture & Offshore Engineering, University of California, Berkeley, June.

Yeung, R. W. (1989), Discussion on "Berechnung des Wellenwiderstands der Practikal Schiffformen" by G. Jensen, Schiffbautechnishe Gesellschaft e.V. Hauptversammlung, (German SNAME, annual meeting), Berlin, Nov. 17.

*Yeung, R. W. & Ananthakrishnan, P.(1989). "Nonlinear Solution of Nonlinear Wave and Wave Body Interaction Problems using a New Method of Boundary-fitted Coordinates", *Proceedings*, 4th Int'l Workshop on Water Waves & Floating Bodies, May 2-8, Oystese, Norway.

*Yeung, R. W. & Sphaier, S. H. (1989) "Wave-Interference Effects on a Truncated Cylinder in a Channel", *J. of Engrg Mathematics*, vol. 23, pp. 95-117.

Yeung R. W. & Vaidhyanathan, M. (1990) "Wave Diffraction over Submerged Obstacles", *Proceedings*, 5th Int'l Workshop on Water Waves & Floating Bodies, Manchester, England, March.

*Yeung, R. W. & Wu, C-F. (1989a). "Nonlinear Wave-Body Motions in a Closed Domain", *Computers & Fluids*, vol 17, no. 2, 351-370.

*Yeung, R. W. & Wu, C.-F. (1989b) "Über nichltlineare Wellenbewegung in einem geschlossenen Gebiet", *Jahrbuch der Schiffbau-technischen Gesellschaft*, Band 83, pp. 29-41.

Asterisked items are distributed according to the supplementary distribution list supplied by ONR.

4. Awards

R. W. Yeung was awarded a Humboldt Prize of U.S. Distinguished Senior Scientist for teaching and research accomplishments in 1988. The award was presented by the Alexander v. Humboldt Foundation of Germany, in Bonn, February, 1989.

On behalf of all participants (faculty, students, visiting scholars) of the research activities, I would like to express our gratitude to ONR for its support and encouragement during this period, without which, much of the original findings reported in the publications and dissertation would not have been possible.

Submitted by

Ronald W. Yeung

Prof. Ronald W. Yeung
Principal Investigator

Encl:
4 dissertations (sent Third Class)
9 technical papers (asterisked items)

cc:
1 copy of letter report attached
ORS- S. Kempton (w/o encl.)
SPO- P. Gates (w/o encl.)
ONR Res. Rep. - Linden Clausen (w. papers)